Einstein's hidden worlds

Joe Lykken
Fermilab/University of Chicago

outline

- a cup of coffee
- the hidden world of the atom
- the hidden world of the quantum
- the hidden worlds of spacetime
- the fathers of extra dimensions
- string theory
- braneworlds
- extra dimensions in the laboratory

cafe odeon

plotting revolutions

which revolution was bigger?

the importance of mystery

one cannot help but be in awe
when he contemplates the mysteries of eternity,
of life, of the marvelous structure of reality.
It is enough if one tries merely to comprehend
a little of this mystery every day.

- A. Einstein

science reveals

science is the disciplined application of
our curiosity towards understanding
“the marvelous structure of reality”

the history of science is a history of people
driven by mysteries to reveal hidden layers
and hidden connections

the hidden world of the atom

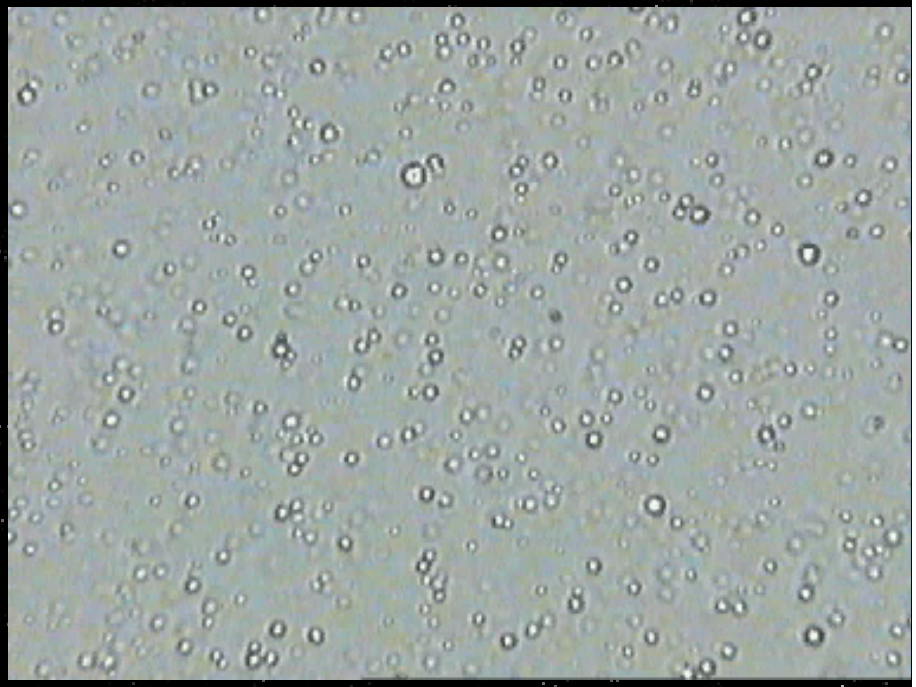
- in 1905, many skeptical physicists (e.g. Ernst Mach) still did not believe in the reality of atoms

- after all, they were invisible!

- then Einstein wrote a short paper (his 3rd of that year) entitled "Uber die von der molekularkinetischen Theorie der Warme geforderte Bewegung von in ruhenden Flussigkeiten susspedierten Teilchen"

the hidden world of the atom

- Einstein explained a mystery seen by botanist Robert Brown
- tiny grains of pollen in water, seen under a microscope, appeared to dance around as if they were “alive”
- Einstein showed that this motion was caused by collisions with even tinier invisible molecules of water



atoms are real

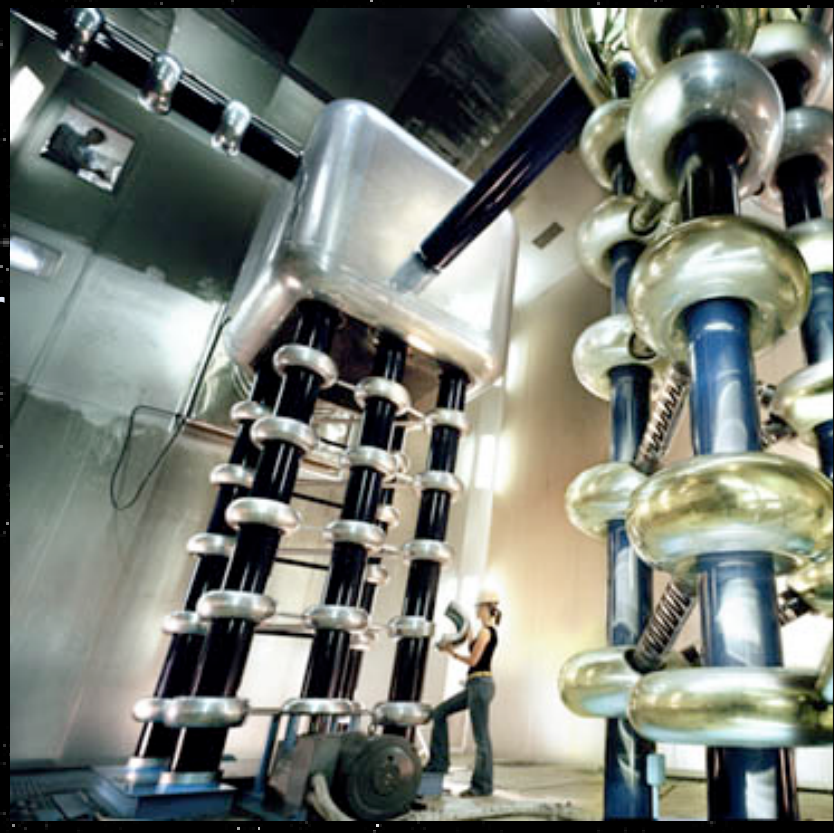
basic science

- Einstein was a theoretical physicist working on the frontiers of basic science
- new concepts like “atoms are real” or $\mathbf{E = mc^2}$ end up having big impacts on our everyday lives
- but basic science is really about ideas, ideas that resolve mysteries and give us a better intuitive understanding of the world around us

ideas and technology

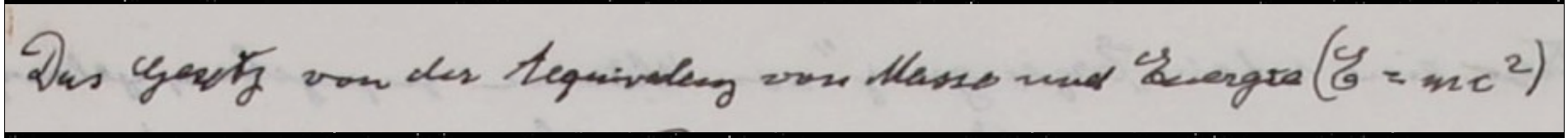
- of course, intuitive understanding is often a big short-cut to getting the technology as well

- e.g. once you realize that lightening is electricity, its obvious that you should be able to scale up your Leyden jar into something more useful:

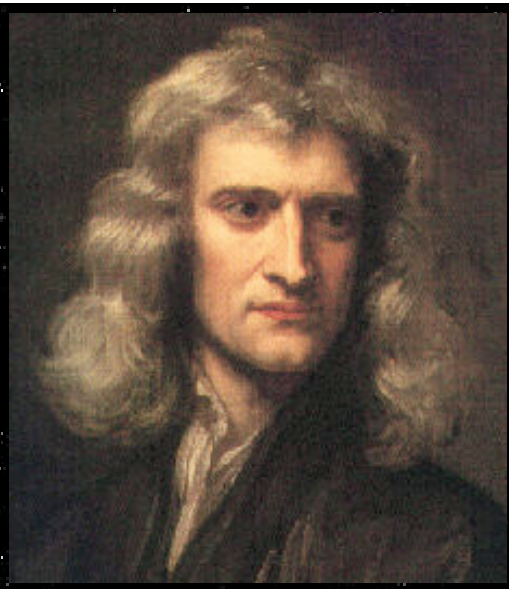


connections have consequences

- When Einstein wrote his $\mathbf{E = mc^2}$ paper in 1907, he knew immediately the potentially ominous implications of this seemingly abstruse connection
- *"if every gram of material contains this tremendous energy, why did it go so long unnoticed?"*

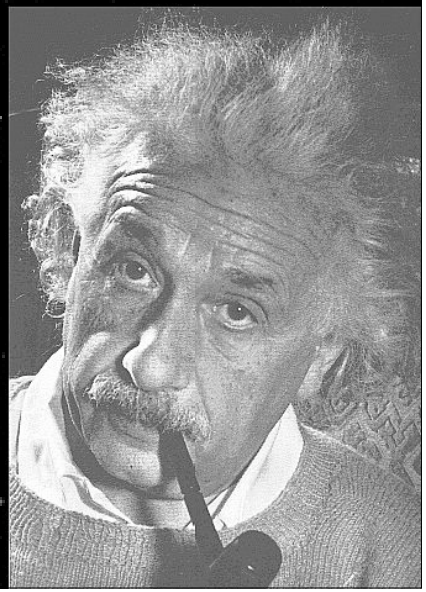


codes of structure and order



- In the 17th century, Rene Descartes tried to explain the mechanism that made the moon go around the earth in terms of invisible vortices
- Newton said: forget about the mechanism for now, and just try to figure out what are the mathematical equations and rules for gravity resulting from of the unknown mechanism

- Newton's strategy was trying to decipher the mathematical codes of the hidden phenomena that shape the universe
- this strategy was wildly successful and has dominated physics ever since
- figuring out the hidden phenomena themselves is much more difficult
- for gravity, it was 250 years before Einstein explained it as the warping of space



the hidden world of the quantum

- Einstein's first 1905 paper was ostensibly about the photoelectric effect, which powers solar cells
- actually what Einstein really did (in 17 pages) was invent and prove the idea of a hidden quantum world

- Max Planck had already talked about the quantum nature of matter, but this didn't seem revolutionary since matter was already supposed to be made out of discrete atoms
- Einstein said that light, despite its obvious wavelike nature, was also made out of discrete quantum bits, later named "photons"
- but Einstein was never happy about the quantum revolution...

mathematics versus understanding

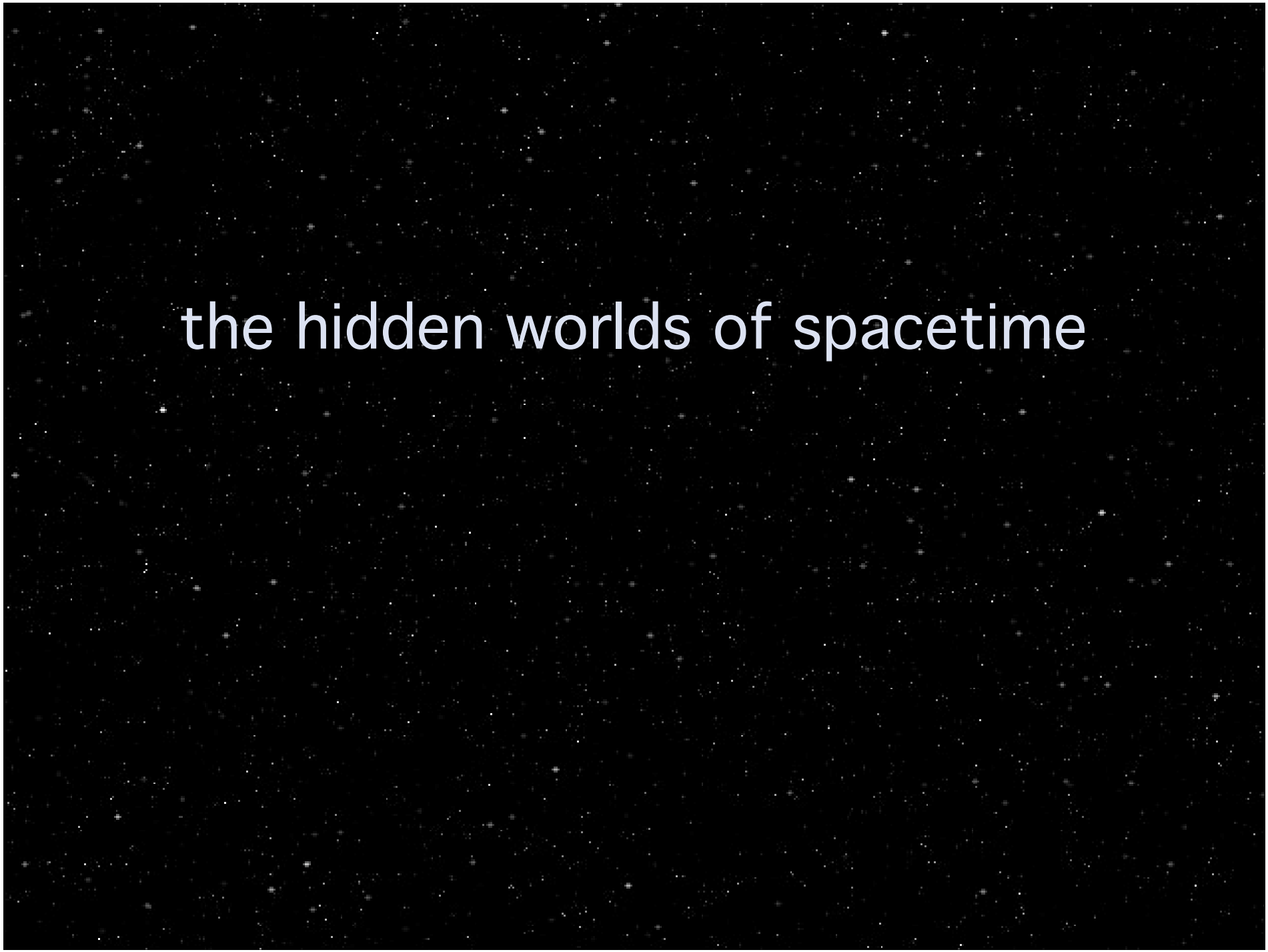
- as a mathematical description of the microscopic world, we know that quantum mechanics is correct
- we have verified it at Fermilab in millions of detailed measurements
- you verify it every time you turn on your Motorola Razr

mathematics versus understanding

"except for the math involved,
all physical theories should be
simple enough for a child to grasp"

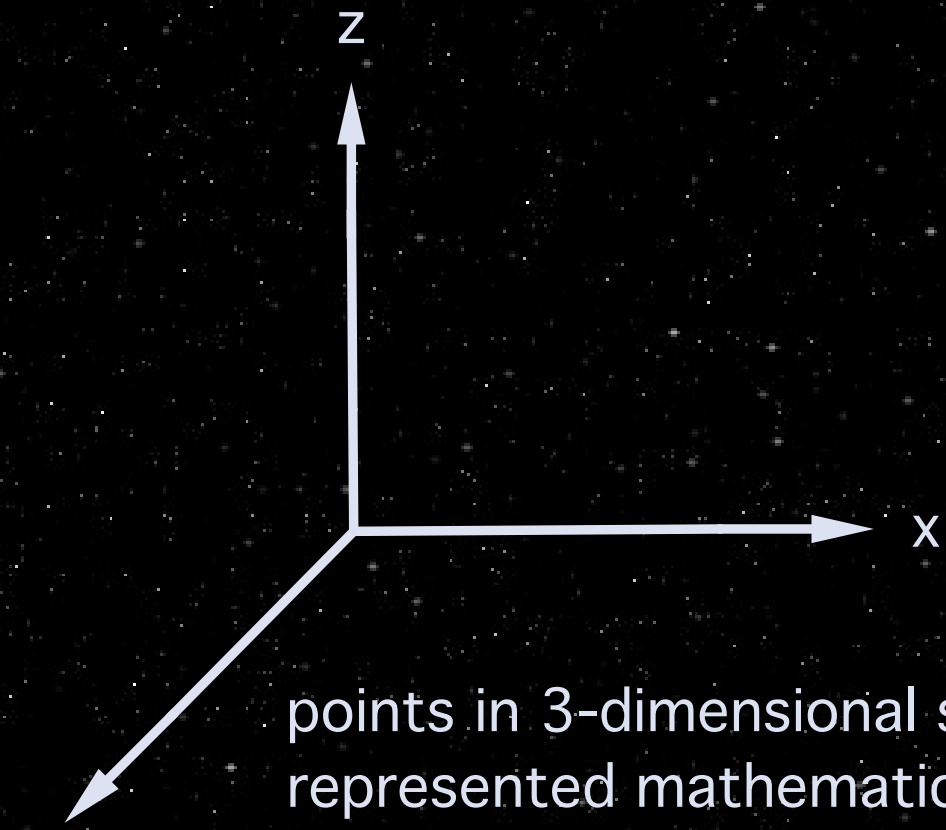
- but we don't understand what the quantum world really is
- anybody who tells you they understand quantum mechanics intuitively is either lying or bluffing

- one of these days somebody will do for for the quantum world what Einstein did for gravity: explain it!
- this could come from physicists studying dark energy or the Higgs particle, objects that don't seem to obey ordinary quantum rules
- it could come from physicists studying the quantum nature of gravity, or black holes
- it could come from physicists studying weird quantum effects, like quantum teleportation


the hidden worlds of spacetime

what is a dimension?

Rene Descartes

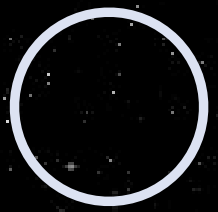


points in 3-dimensional space
represented mathematically by
their Cartesian coordinates x,y,z

the power of analytic geometry

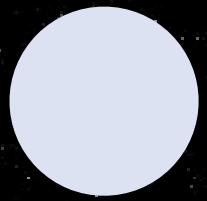
equations replace pictures:

$$x^2 + y^2 = 1$$



circle

$$x^2 + y^2 + z^2 = 1$$



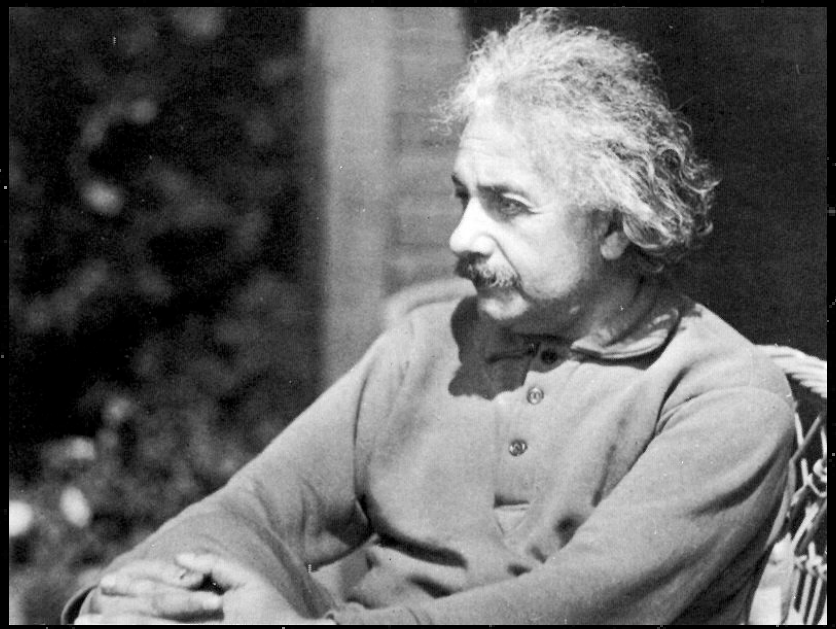
sphere

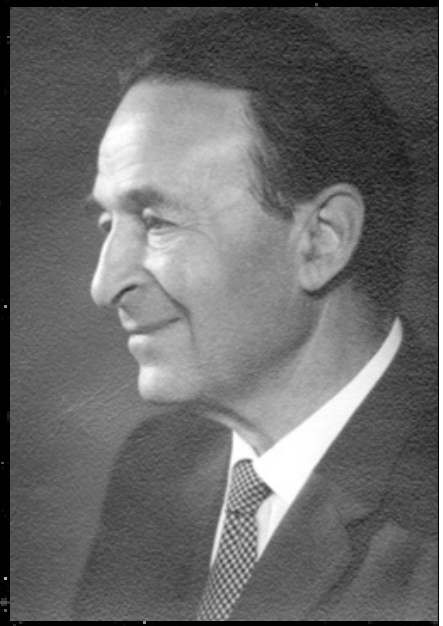
$$x^2 + y^2 + z^2 + w^2 = 1$$

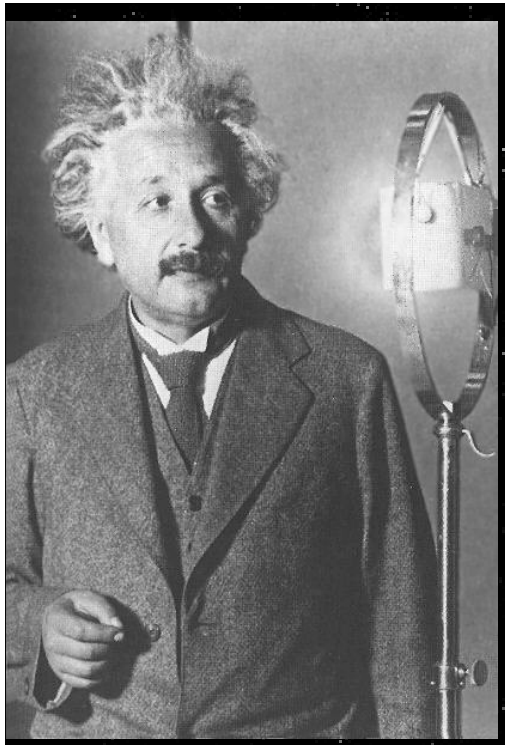
hypersphere

- extra dimensions make sense in mathematics
- do they also make sense in physics?
- could there be more physical dimensions than the three that we see?
- if so, why are the extra dimensions hidden?
- and what are they good for?

the fathers of extra dimensions



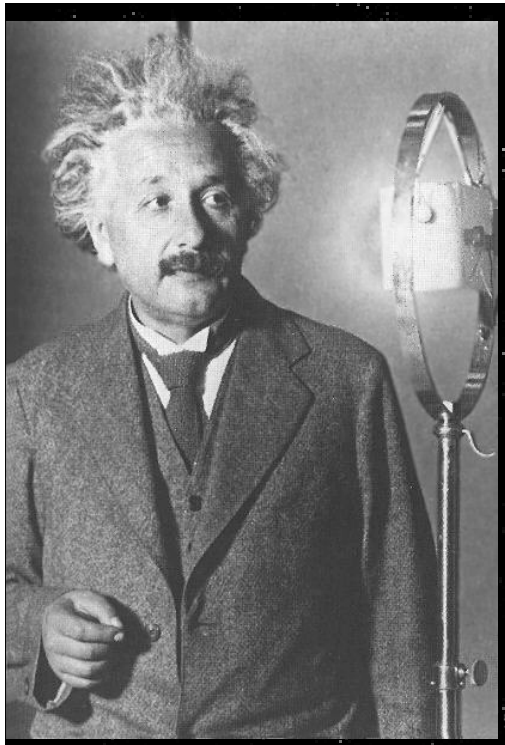




“time is the fourth dimension”

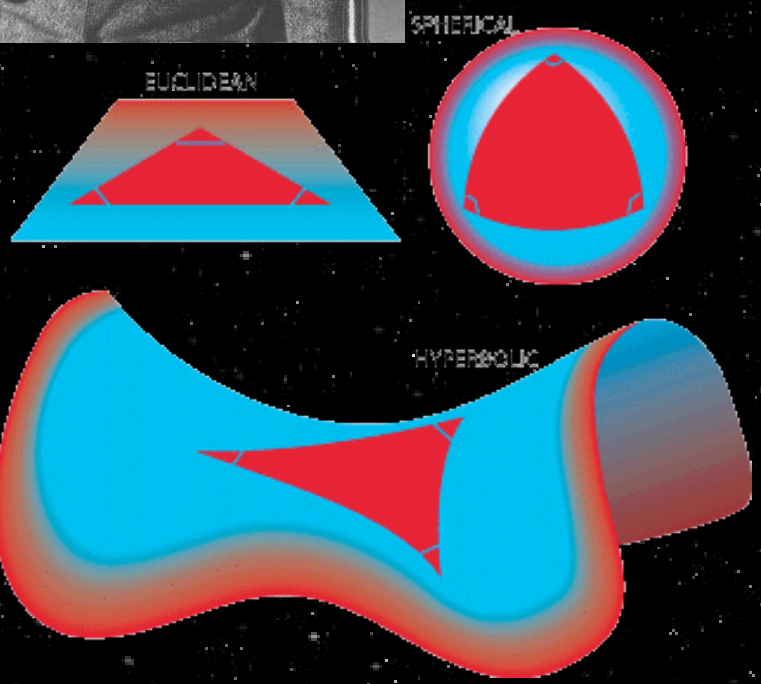
A. Einstein, 1905

- four dimensional space-time: x,y,z, and t
- there is a universal constant, called “c”, which converts measurements of time into measurements of space.
- c = 299,792 kilometers per second



“space has a shape”

A. Einstein, 1911

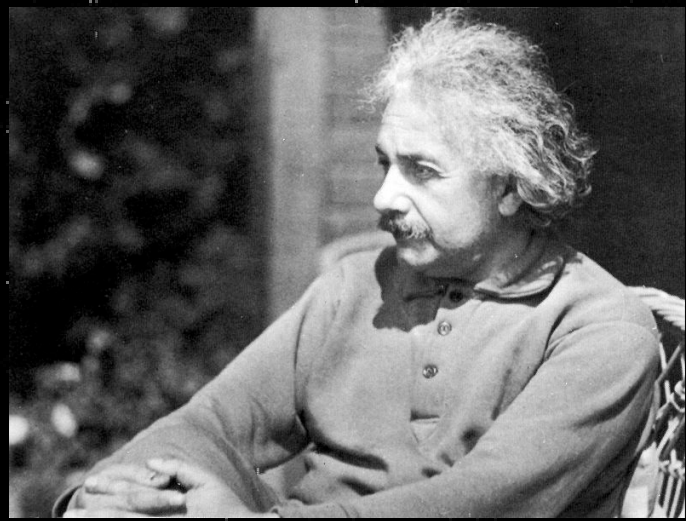


- the curvature of space is revealed by measuring the total angle inside a triangle
- the shape of space is determined by matter and energy
- gravity is nothing more than curvature of space

the fifth dimension

in 1914, Finnish physicist Gunnar Nordstrom showed that gravity and electromagnetism could be unified as a single force, in a theory with an extra spatial dimension

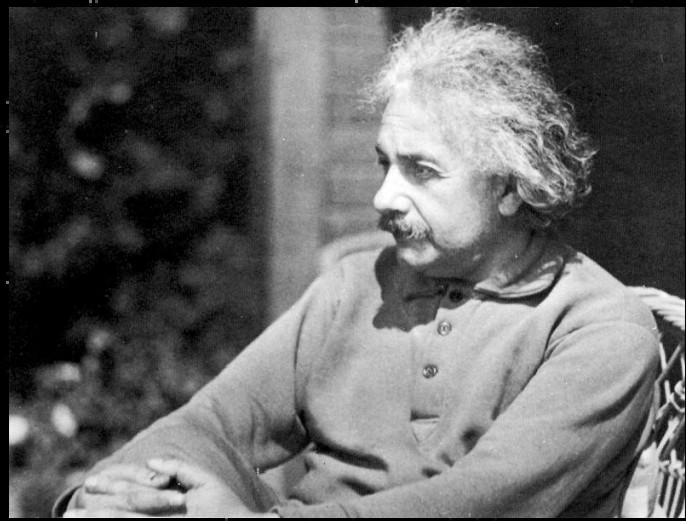
Einstein ignored Nordstrom's idea, probably because it used Nordstrom's own theory of gravity, which was then in competition with Einstein's



the fifth dimension

in 1919, Polish mathematician Theodor Kaluza again introduced the idea of a fifth dimension, but this time using Einstein's theory of gravity - this made all the difference:

"The idea of achieving [a unified theory] by means of a five-dimensional cylinder world never dawned on me... At first glance I like your idea enormously"

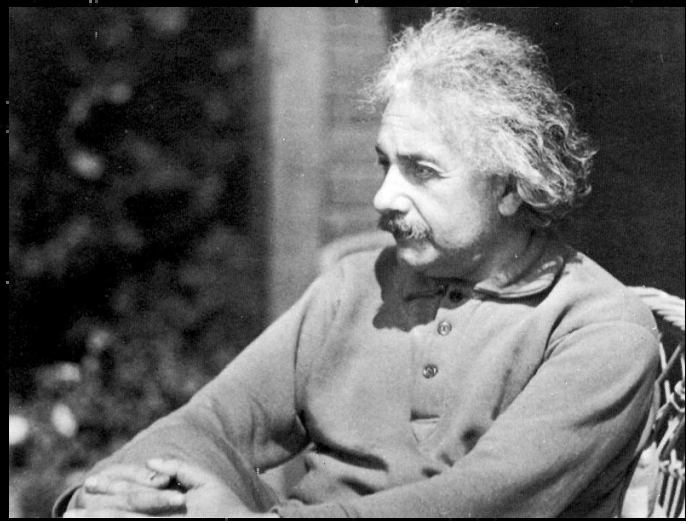


the fifth dimension is a circle

Nordstrom, Kaluza, and Einstein all assumed that the fifth dimension wasn't real, since otherwise why don't we see it?

in 1926, Swedish physicist Oskar Klein proposed that the fifth dimension was real, but too tiny to see

"Klein's paper is beautiful and impressive."



A simple example:

the tightrope walker sees the tightrope as having only one spatial dimension

the tightrope walker can only move in one direction, (back and forth)

the extra dimension is a circle?

but an ant on a tightrope
can move both back and forth
AND around a circle

the ant sees an extra dimension
= an extra tiny circle at every point
along the tightrope

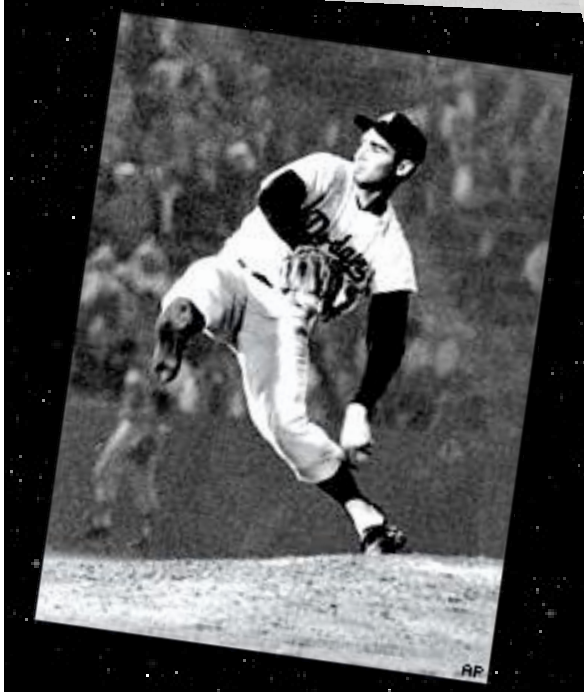
the fifth dimension is a circle

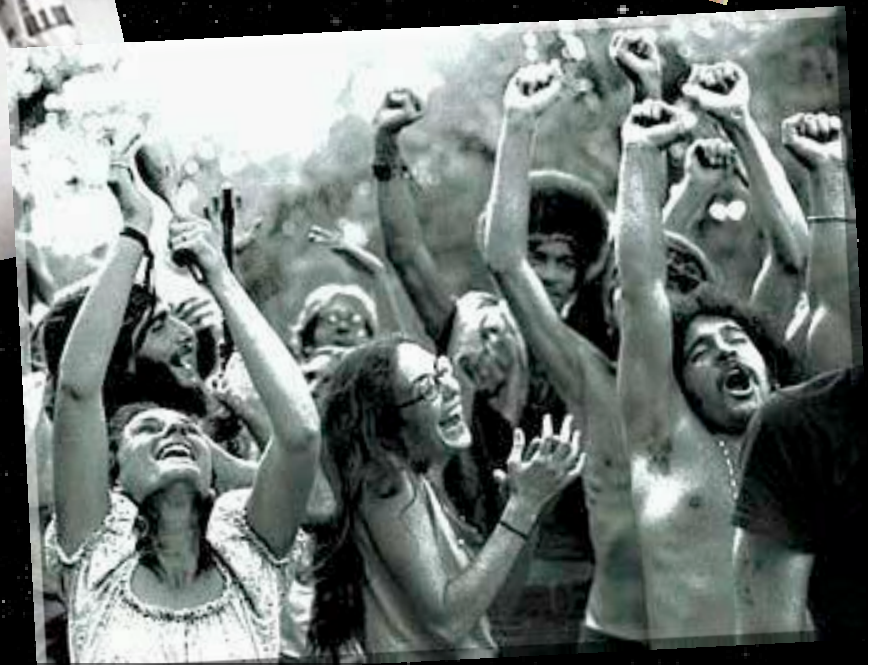
Klein computed how small the circle of the 5th dimension should be, in order to give a unified theory of gravity and electromagnetism

the answer is:

.00000000000000000000000000001 centimeters

nobody thought about extra dimensions for 50 years





string theory

John Schwarz

in the 1970s some
visionary physicists began
to construct a
radical new theory

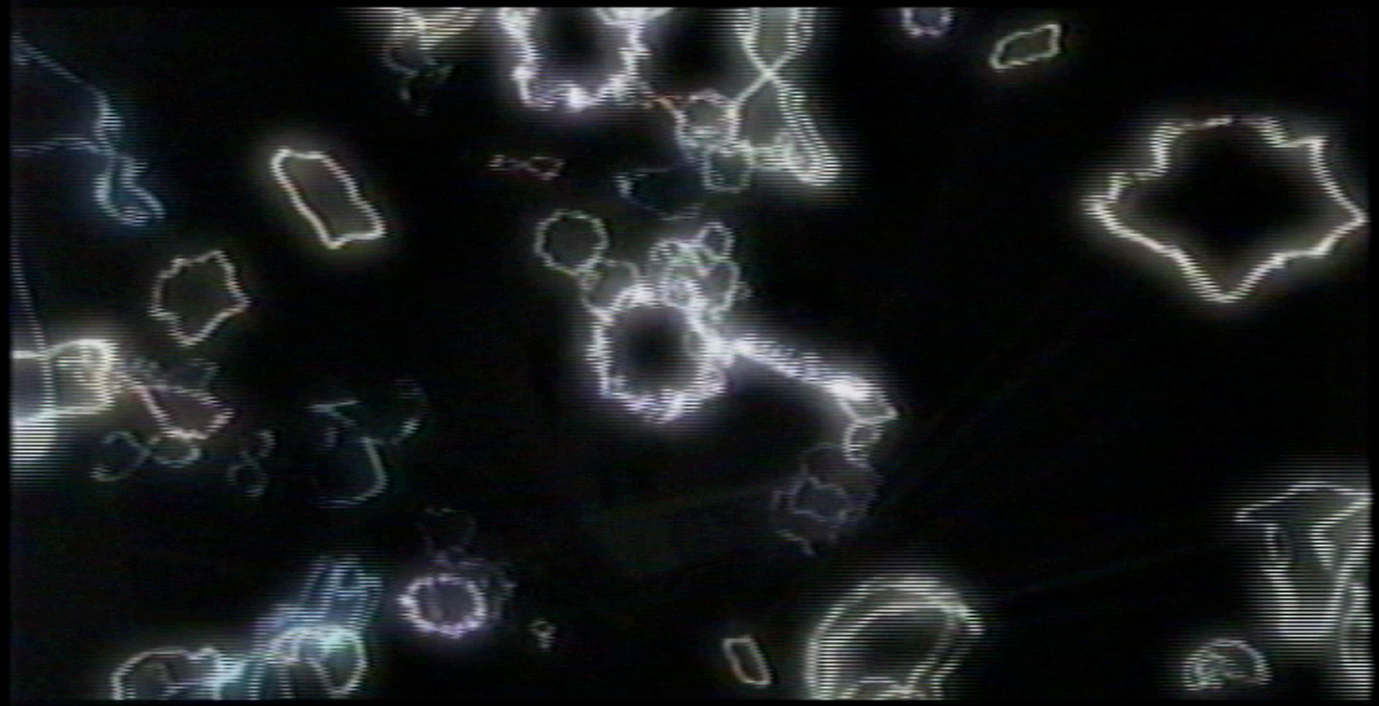
Pierre Ramond

in this theory all of the
elementary particles are
just different vibrations of
microscopic strings

Gabriele Veneziano

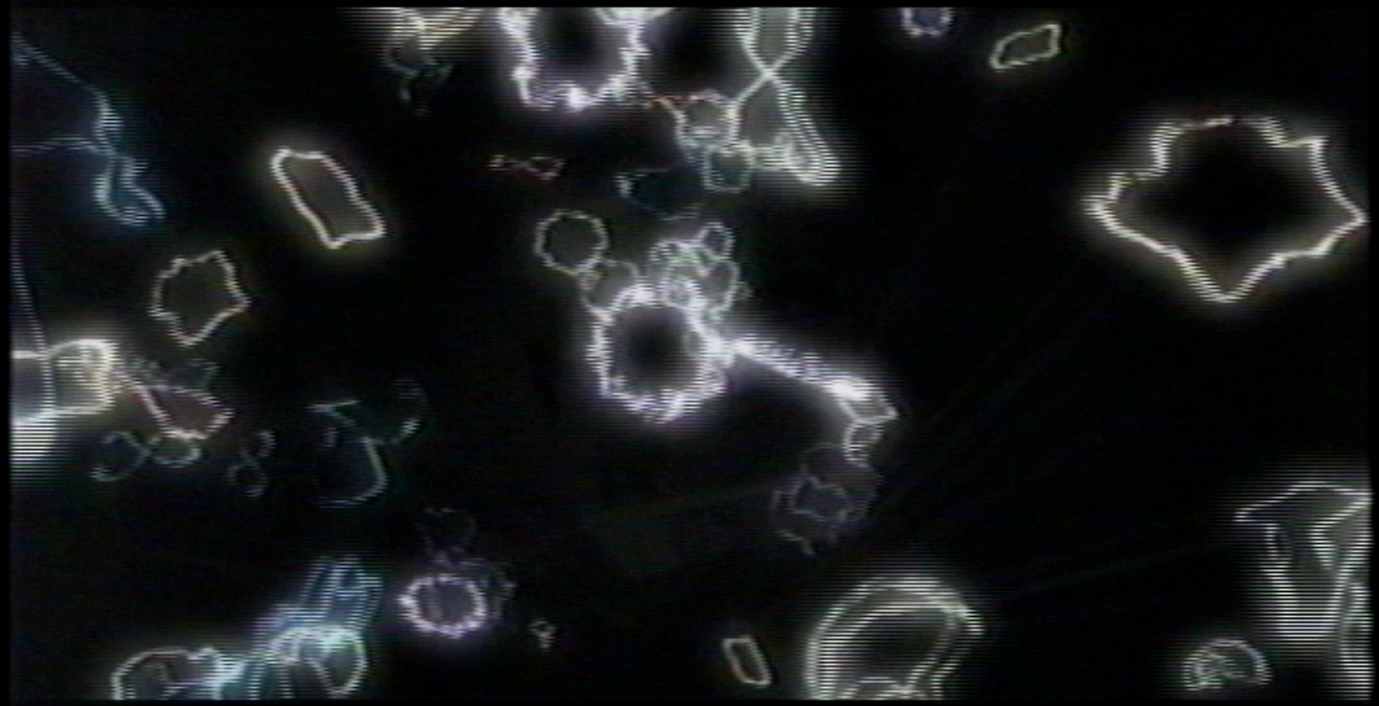
in string theory

electrons, quarks, photons, gravitons, neutrinos, etc are all different vibrations of one kind of microscopic string: the superstring



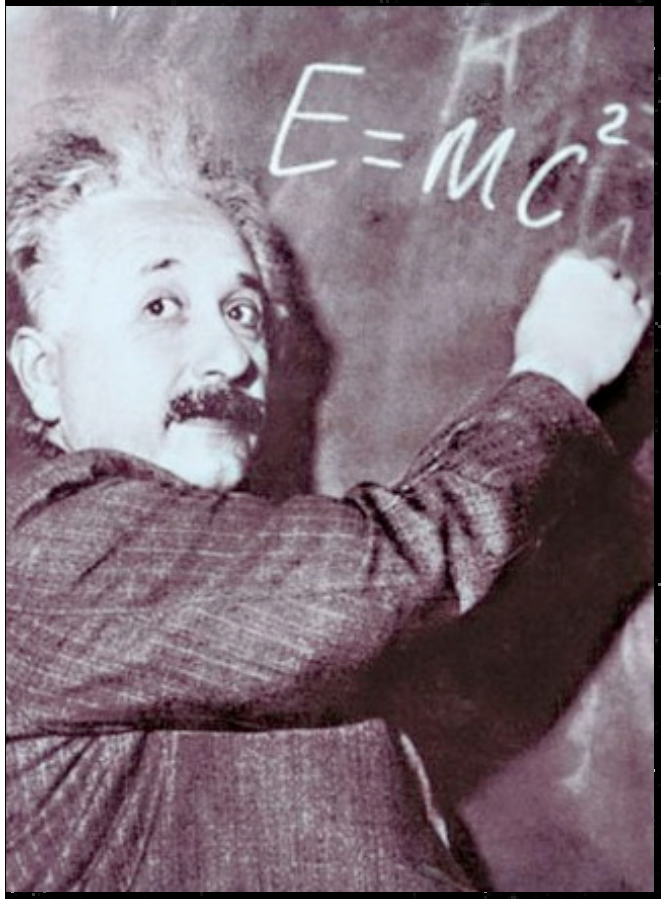
quantum strings

superstrings stretch themselves by wiggling.
quantum mechanics says that a microscopic string
will always be wiggling, at least a little bit



particles from strings

- to us, a microscopic wiggling string looks like a particle, because the string is too small for us to notice either its size or its wiggles
- the momentum of the string vibrations, and the energy of the string stretching, will look to us like the mass of the “particle”
- this mass can be computed from Einstein’s famous formula:



actually we need the more complete version of this formula:

this formula tells us the mass of a "particle" in terms of the energy and momentum of the vibrating superstring

$$\mathbf{E^2 - (p_x c)^2 - (p_y c)^2 - (p_z c)^2 = (mc^2)^2}$$

John Schwarz

one small problem:
some elementary particles (the photon, the graviton) are massless

for superstrings, this requires a delicate cancellation between the energy and momentum of stretching and vibration

in the original version of string theory, the cancellation didn't work!

$$\mathbf{E^2 - (p_x c)^2 - (p_y c)^2 - (p_z c)^2 \neq 0?}$$

John Schwarz

only two ways to modify the quantum vibrations of a string:

- invoke supersymmetry, which reduces the quantum wiggles
- increase the number of spatial dimensions that the strings can wiggle in

only with 9 spatial dimensions can superstrings produce the particles that we see!

John Schwarz

denied tenure at Caltech

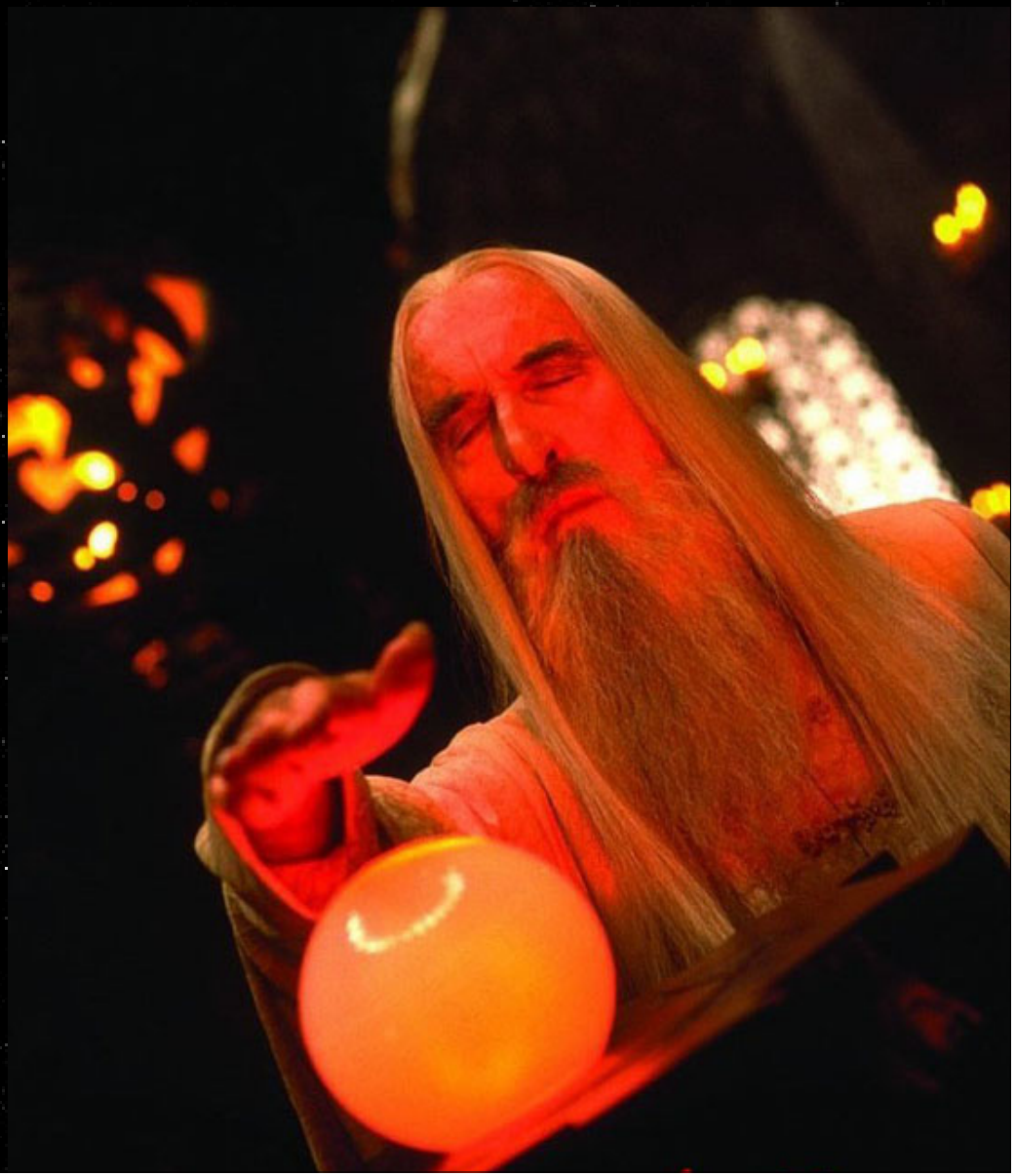
superstrings: a great idea?

Pierre Ramond

fired from Fermilab

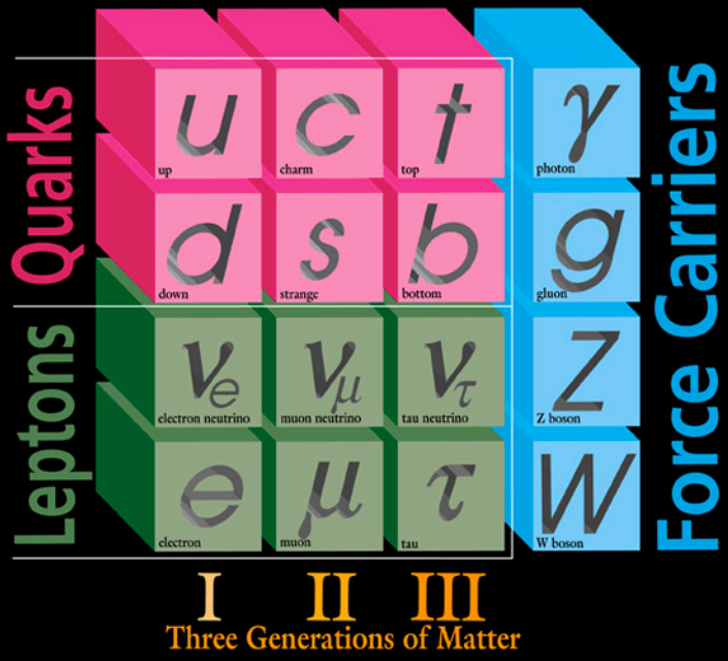
after 10 years of neglect,
string theory finally
became a hot idea in 1984

- string theory is very elegant mathematically
- but if we take string theory seriously, it makes a firm prediction that there are (many) extra dimensions of space
- is this reasonable?



too many particles

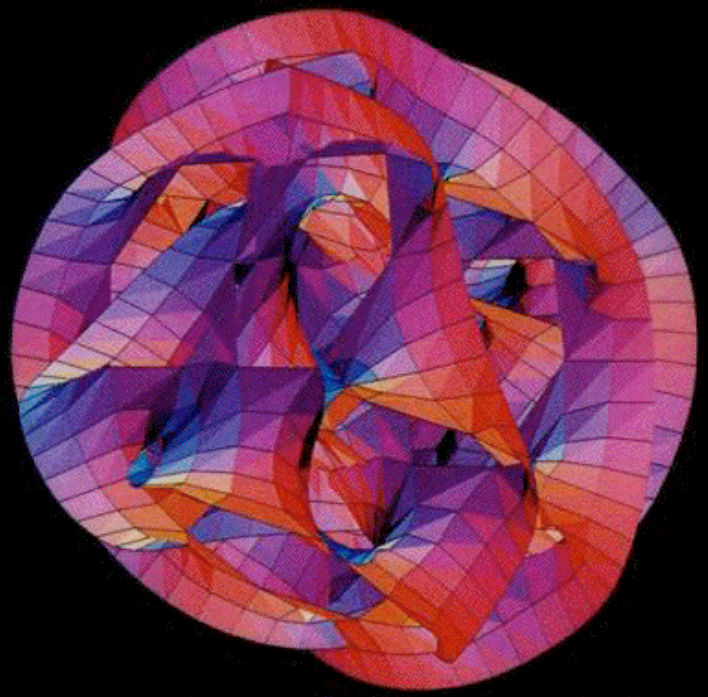
- so far, particle physicists have discovered 57 different elementary particles
- and these 57 particles are related to each other in complicated ways



something is wrong or missing in this picture...

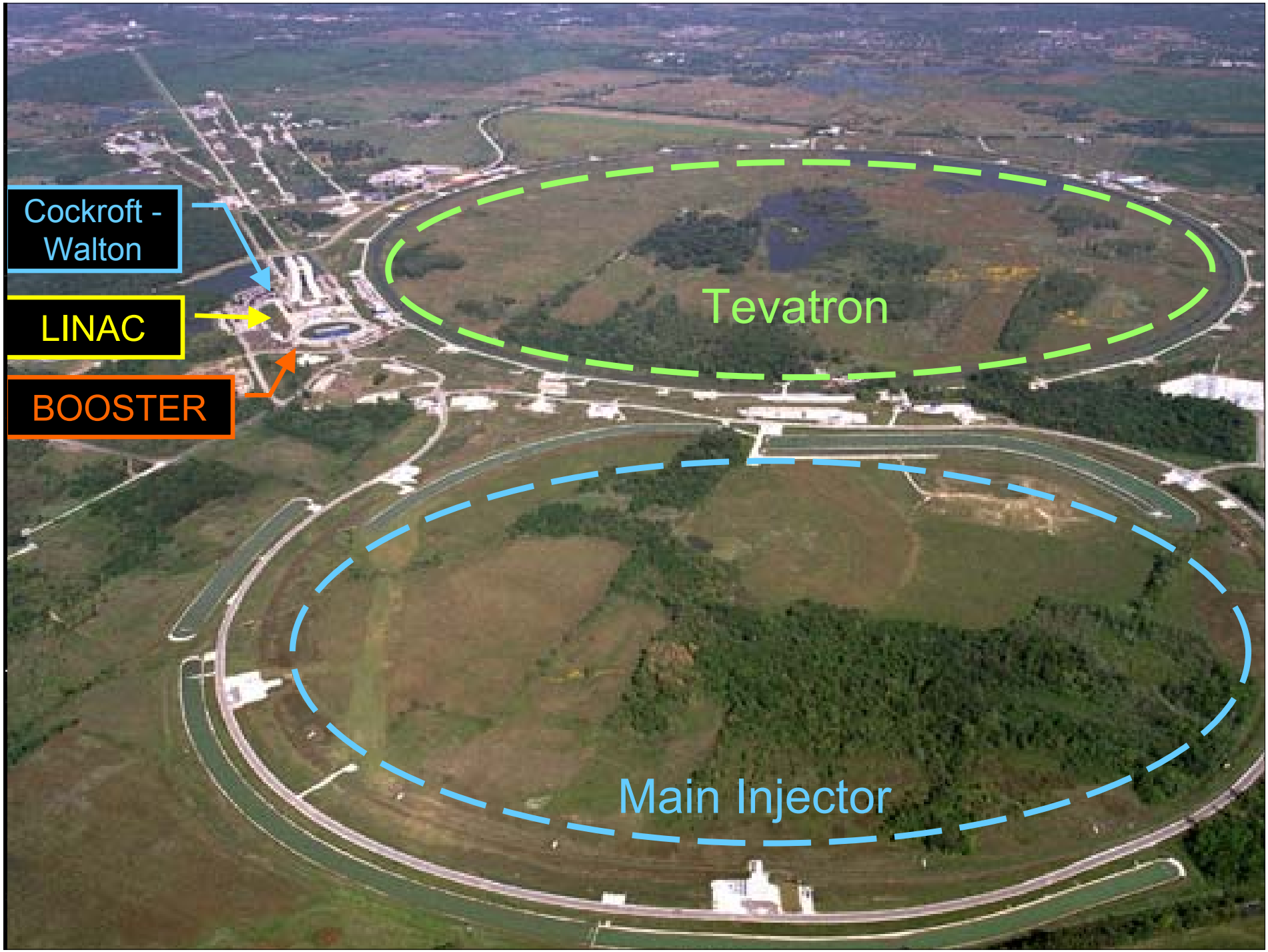
the shape of extra dimensions
may explain the complexities
of particle physics

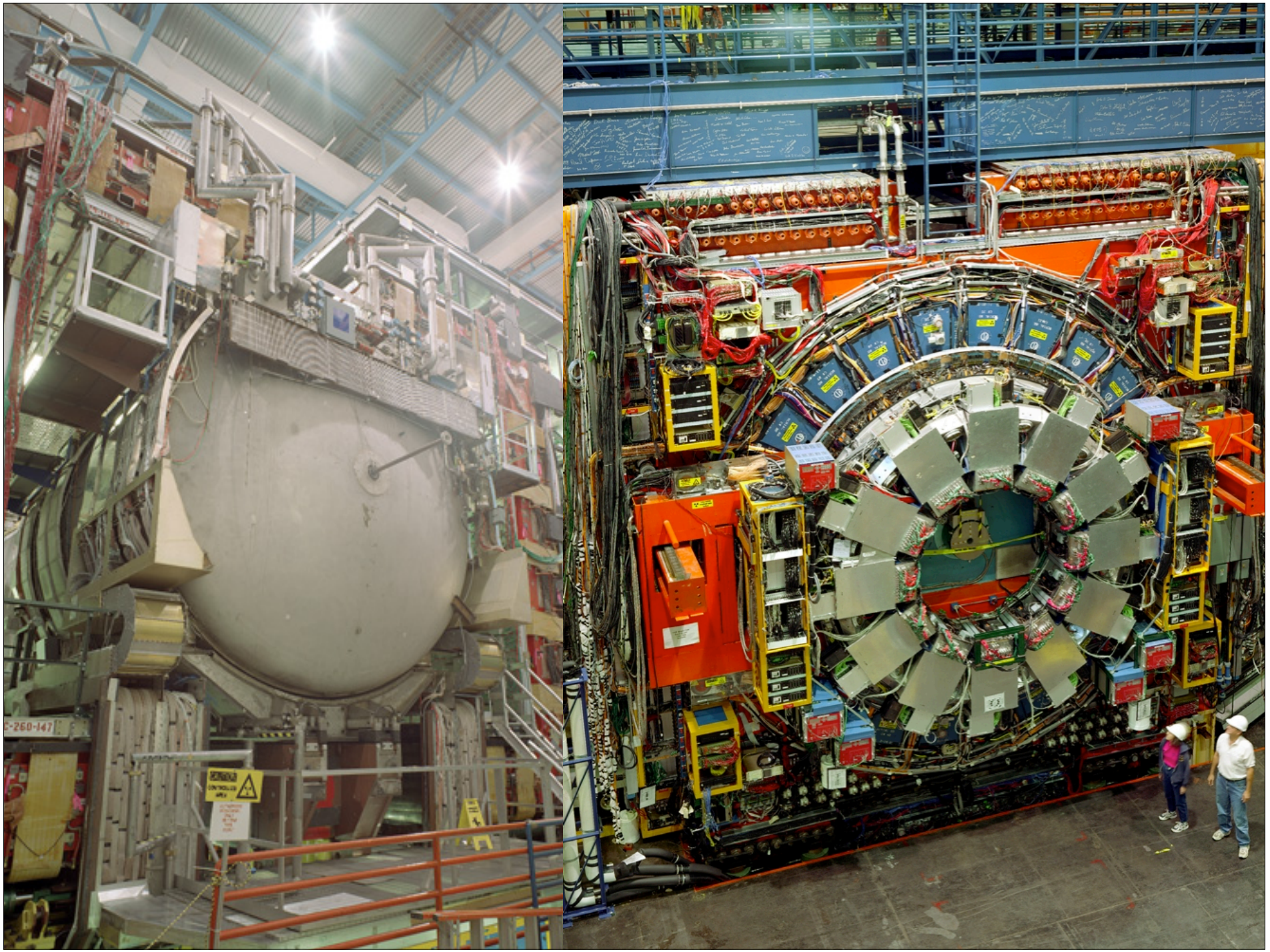
slice of a
6 dimensional Calabi-Yau
manifold



how do you detect an extra dimension?

- even if extra dimensions make sense in theory, it still isn't physics until you find a way to detect them in experiments
- for particle physicists, this means figuring out how to detect particles that move around in the extra dimensions

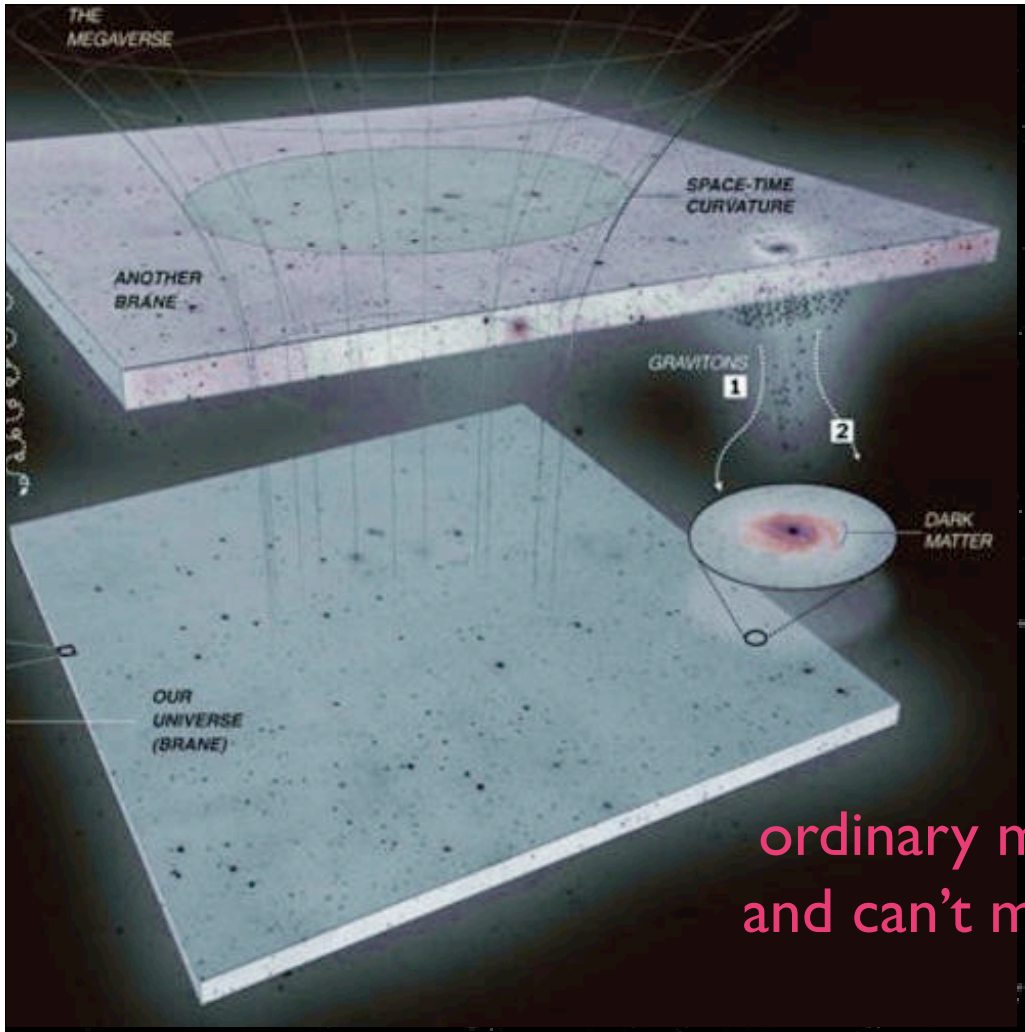

Cockroft - Walton
LINAC
BOOSTER
Tevatron
Main Injector



one small problem:

- we don't know which elementary particles can move in the extra dimensions
- string theory suggests that perhaps none of the particles of ordinary matter can move in extra dimensions!

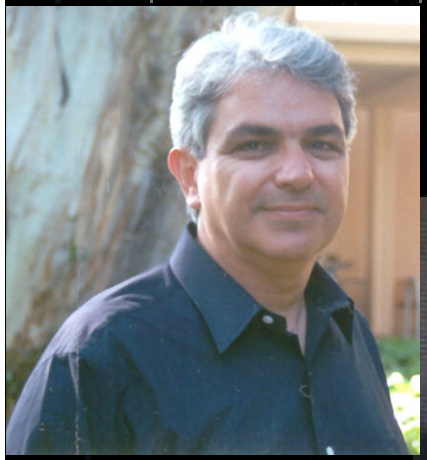
the braneworld



ordinary matter is trapped on a brane
and can't move in the extra dimensions

only gravitons see the full extra dimensional universe

- if the braneworld idea is correct, the extra dimensions may be large!
- then only experiments with gravity or gravitons will detect the presence of extra dimensions

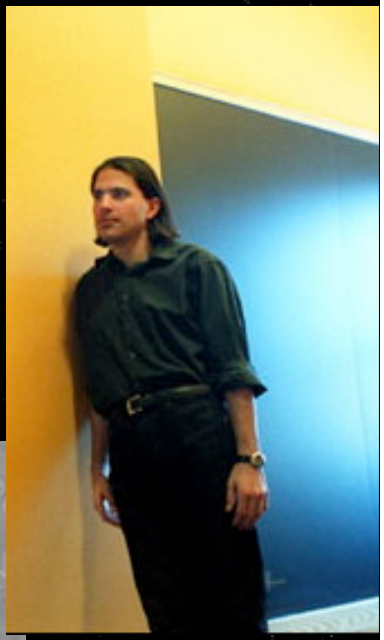


Savas Dimopoulos

Gia Dvali

Lisa Randall

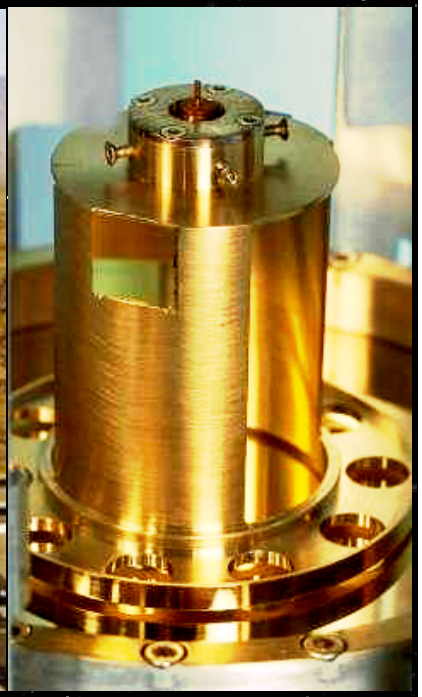
Raman Sundrum



Nima Arkani-Hamed

testing gravity

- telescopes look for gravity's effects on the cosmos
- gravity wave detectors may see ripples in space caused by black hole collisions

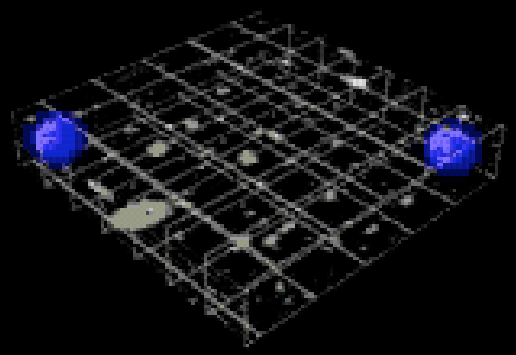


extra dimensions at Fermilab

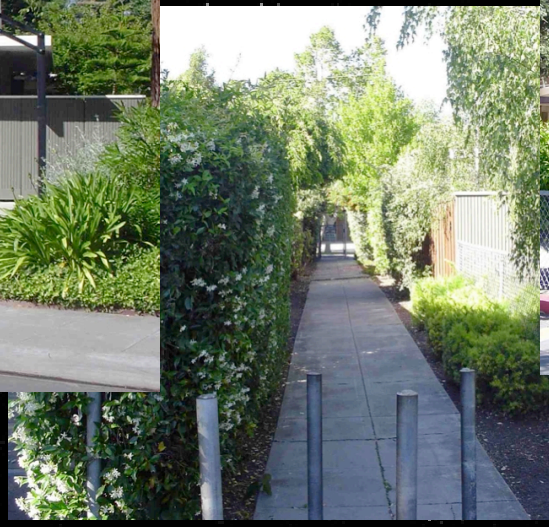
- particle accelerators are our most powerful tools for exploring extra dimensions
- if Klein's idea of tiny extra dimensions is correct, we can detect them as long as their size is no smaller than .00000000000000001 centimeters!
- if the braneworld is correct, we can produce gravitons at particle colliders like the Tevatron

one small problem:

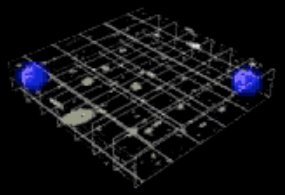
- in the braneworld scenario, the gravitons that we produce will disappear into the extra dimensions:



shoes in extra dimensions



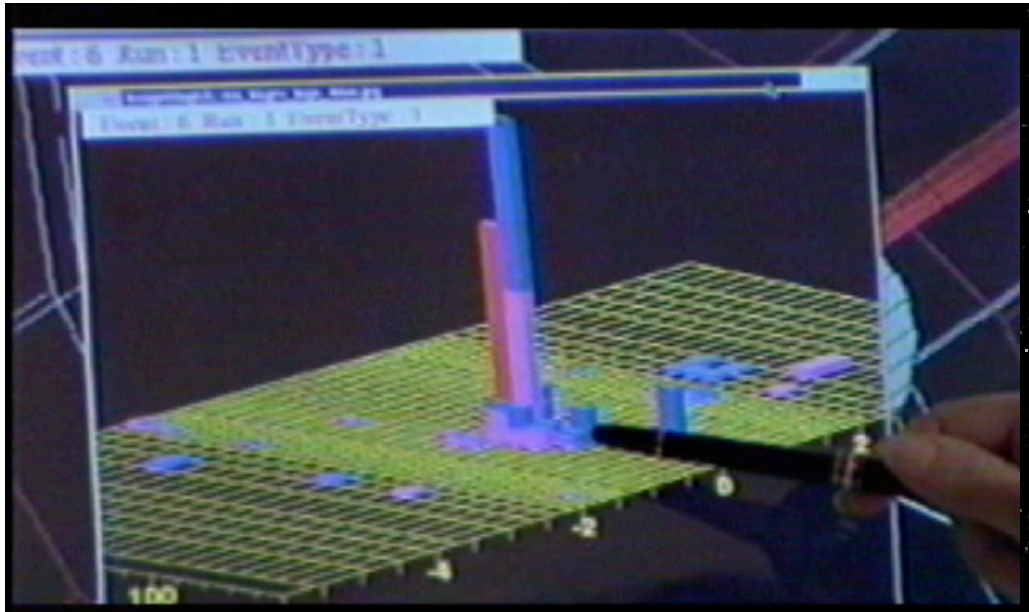
shoes in extra dimensions



an experimental challenge

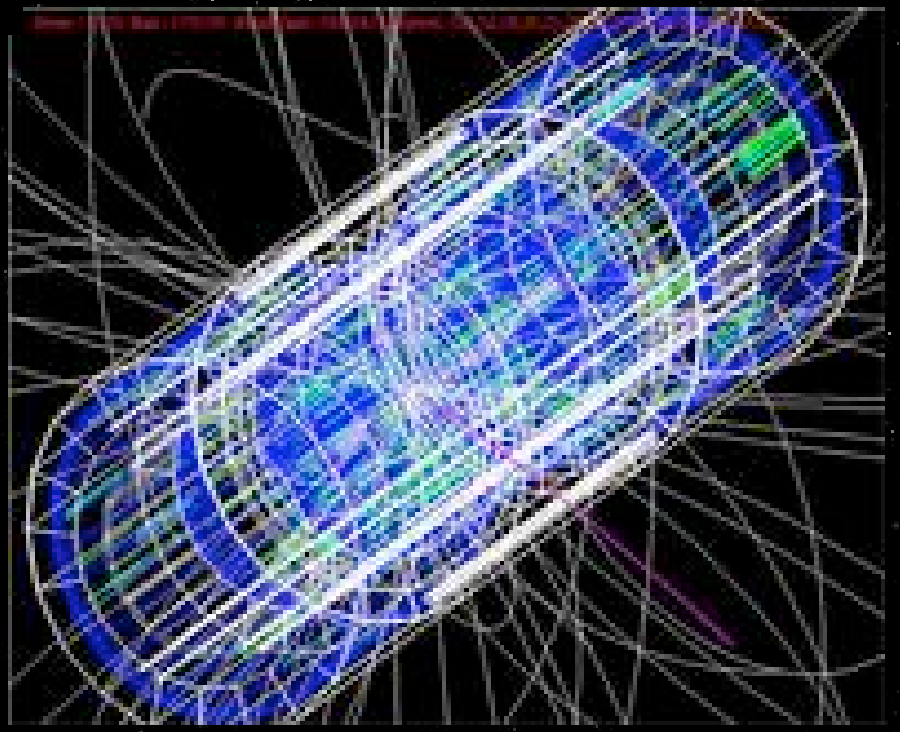
Maria Spiropulu

Greg Landsberg

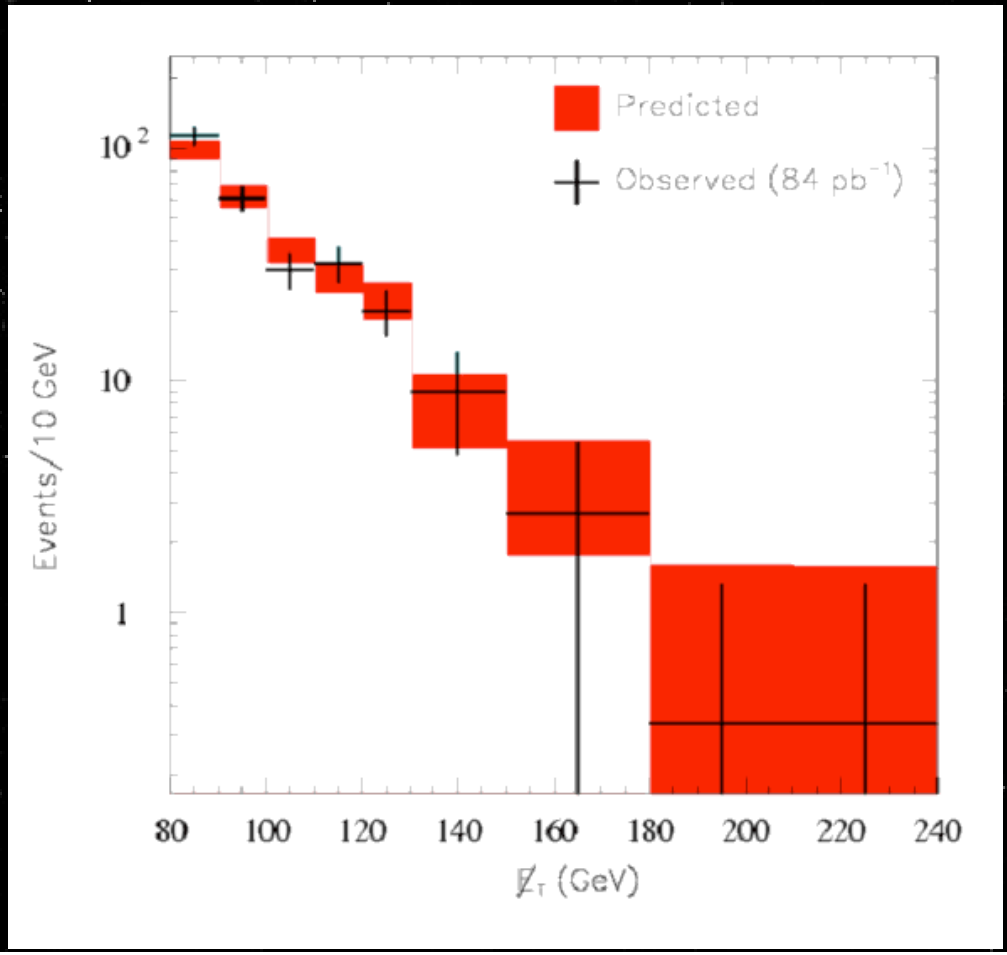


you have to sift through trillions of “events”

to find the rare events that have new particles or new physics



what does the Tevatron data show so far?



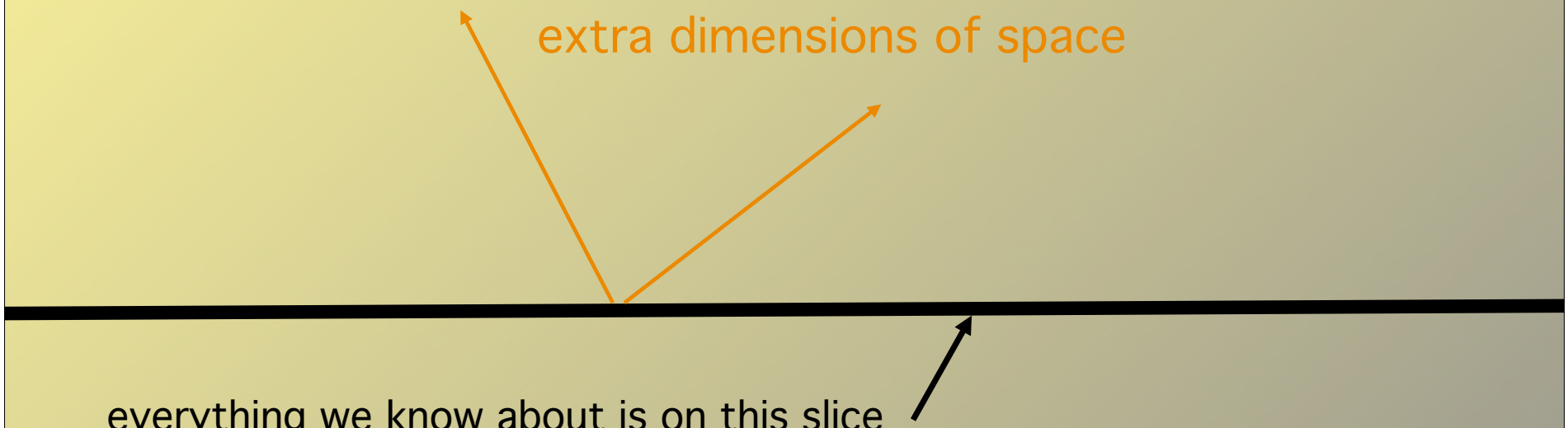
the search continues

LHC collider at CERN turns on in 2007 with 7 times the energy of the Tevatron

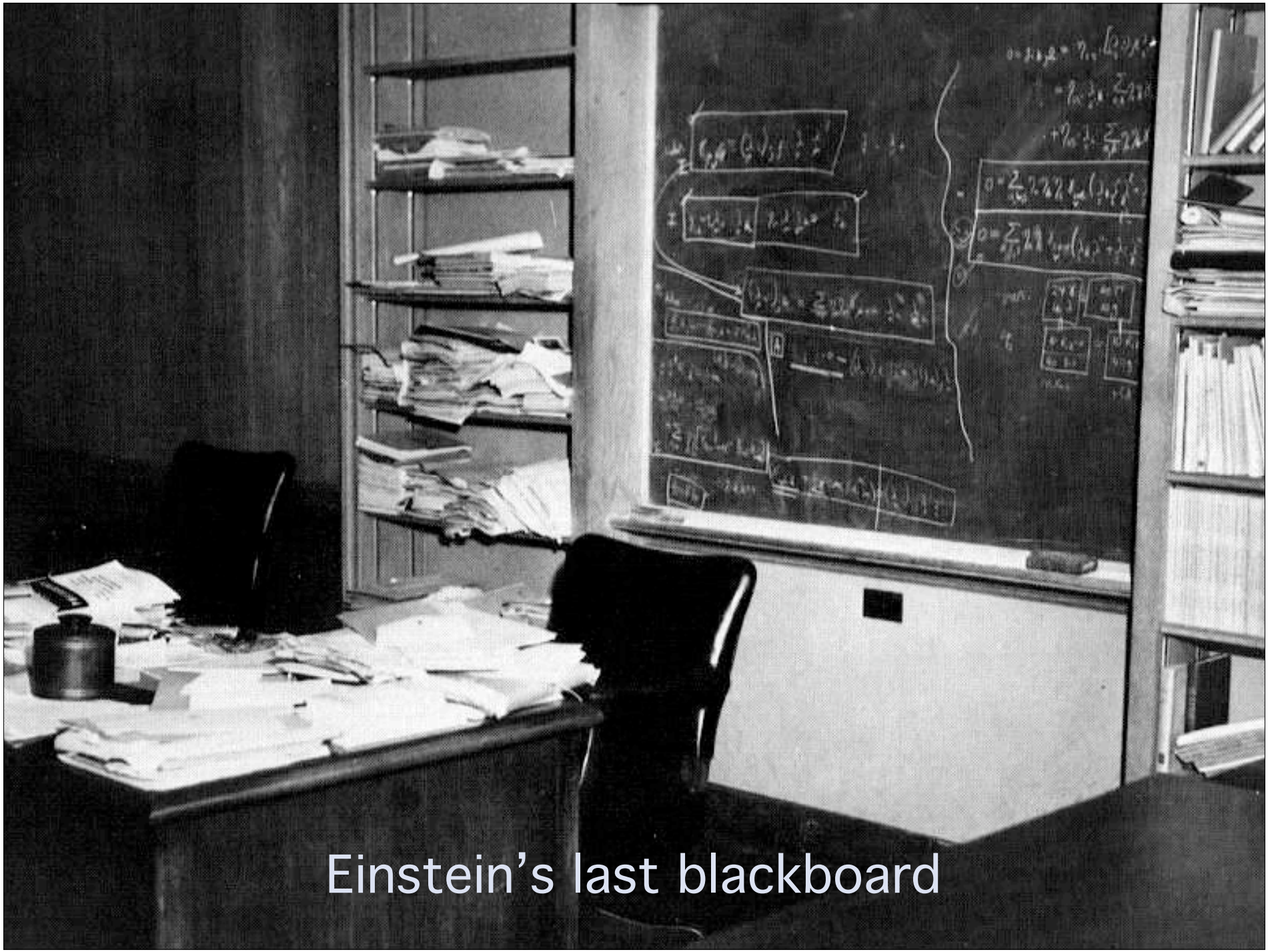
the universe: traditional view

you are here

the universe: a bigger view



the rest is terra incognita



Einstein’s last blackboard